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The use of bio-based materials to reduce the environmental impact of construction

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Abstract. In the UK, the construction industry is responsible for over 50 % of total carbon emissions. 20% of these carbon emissions are embodied within the construction and materials of buildings and the balance is expended in environmental control (heating, lighting, air conditioning) and other 'in use' aspects of occupation of buildings. This is replicated in other countries to a similar extent. This lecture identifies ways in which the use of bio-based construction materials can significantly reduce the environmental impact of the construction sector, including the impact of the use of renewable materials, CO₂ sequestration through photosynthesis, passive environmental control, replacement of high impact construction materials and retro-fit.

1 Introduction

The built environment is responsible for over 50% of the UK's total carbon emissions [1], and other developed countries have a similar responsibility.

The targets set out in the UK by the Code for Sustainable Homes [2], the Kyoto Protocol [3], the 2016 Zero Carbon Policy [4] and the Low Carbon Construction Action Plan [5], demand reductions in the embodied carbon of building materials, since they contribute 10% of the total CO₂ emissions for the whole of the UK across all sectors [1]. The use of buildings (heating, lighting, air conditioning etc...) contribute a further 47% to those CO₂ emissions, so reductions in energy use over the lifetime of the building can make a significant contribution to the mitigation of the effects of climate change.

A number of strategies have been developed to reduce carbon emissions including improved thermal insulation for both new build and retro-fit (e.g. the Green Deal); better building design (e.g. PassivHaus); improved efficiency of heating, ventilation and air conditioning (HVAC) systems; reduction in the carbon emissions of energy production through the use of nuclear energy, renewable energy sources (hydro, wind, tidal, photovoltaic, bio-mass....); but less emphasis appears to be placed on reducing the embodied energy within buildings.

Embodied energy is the energy cost of constructing a building, and since this is a fixed cost which makes up ~10% of total global carbon emissions, it is a significant factor which is worthy of addressing with great urgency.

Traditionally, building materials were sourced locally, and it is the range and variety of local materials which created the character of the historic built environment. Vernacular buildings rely on small-scale craftsman led construction technologies, and such technologies are not suitable for the high volume, mass produced built environment need to service the large and every growing global population. Industrialisation brought financially efficient technologies to the built

environment such as mass produced bricks, concrete and steel. Such materials are low cost to produce and require low skill levels to convert into buildings. They all, however, share a common high energy cost in areas such as extraction, processing and transportation. In addition, these materials all come from finite (if large) resources. Once extracted and converted, the raw material is gone forever, and with low historic levels of recycling, much of this material is lost to future generations who will have to rely on increasingly depleted resources.

Life cycle assessment (LCA) has become an important tool in the design of future construction. This is a vast area of study, with many variants as defined by the various practitioners. All variants share a common approach as defined by ISO14040 [6]. There are three phases to any life cycle assessment: Goal and Scope Definition; Inventory Analysis; and Impact Assessment. These phases are all subject to interpretation, and it is vital that transparency is maintained throughout the process. It is only through this transparency that the validity of any LCA can be assured.

For buildings Figure 1 shows a schematic of the LCA process that is followed.

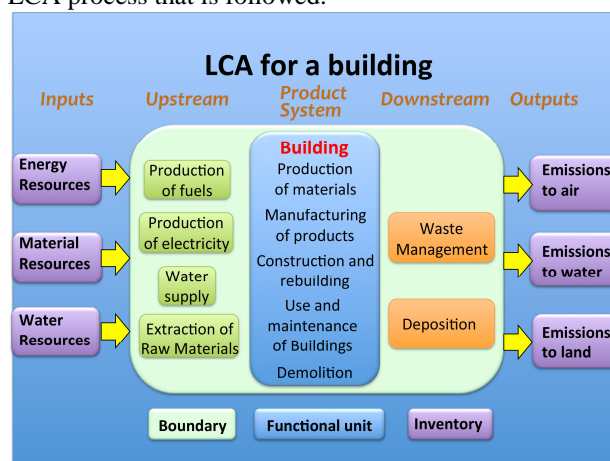


Fig.1 : Schematic for the LCA of a building

The schematic deconstructs the various elements that are involved in the construction, use, maintenance and deconstruction of a building and adds clarity to our understanding of how it is possible to reduce the environmental impact of construction.

This paper examines the impact of the use of bio-based materials on the LCA of a building.

2 Renewable materials

One of the key characteristics of bio-based materials is the fact that they are by nature renewable resources. A renewable resource is a natural resource which can replenish with the passage of time. Provided that the rate of consumption of the resource does not exceed its renewal rate, then that resource can also be considered to be sustainable.

Figure 2 shows the relative impact of different activities within the UK construction industry, which, in 1998, was responsible for total CO₂ equivalent emissions of 28,327 kt.

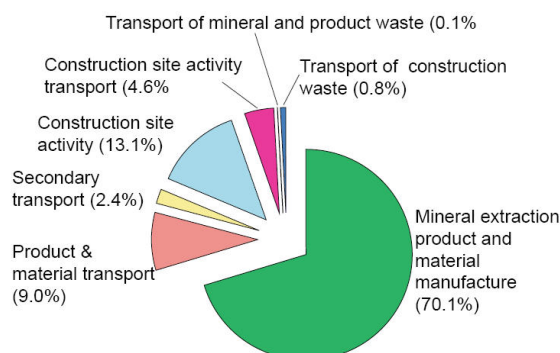


Fig.2 : Breakdown of emissions from the construction industry [7]

It can be seen that over 70% of carbon emissions are associated with the extraction of minerals, product and material manufacture.

Many construction materials (concrete, cement, fired bricks, blocks) use large amounts of energy in their manufacture and transport. Most of this energy comes from the burning of fossil fuels, increasing the amount of CO₂ released into the atmosphere, with the consequent global warming effect.

Construction materials made from crops generally use much less energy in their production, and through the judicious use of locally grown material, can also reduce the transportation energy cost.

There are a range of categories of bio-based materials that can be employed to displace conventional non-renewable materials as shown in Fig.3.

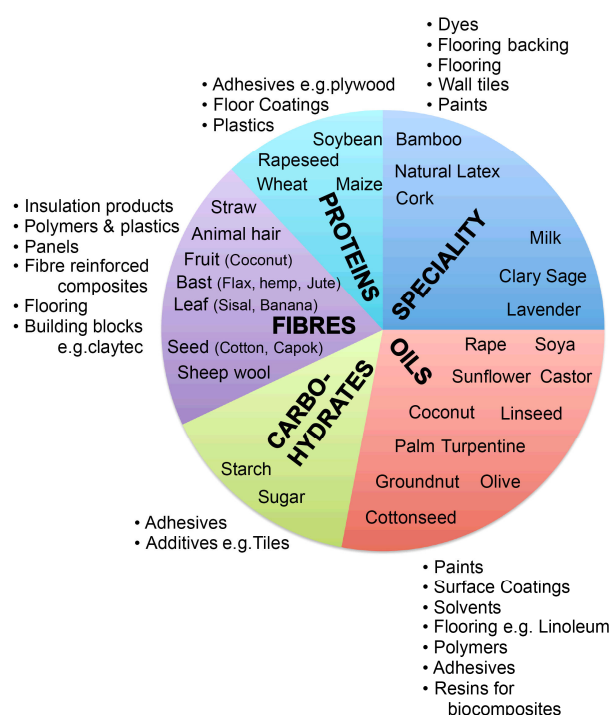


Fig.3 : Bio-based materials by source [8]

2.1 Insulation

Bio-based insulation materials have lower embodied energy than conventional non-renewable alternatives. These materials are all biodegradable, so that at end of life they cause much less pollution. Unlike glass fibre, and mineral wool, these materials are non irritant which makes them much more user friendly. Thermal conductivity of insulation materials such as Sheep's wool, flax and hemp fibre is around 0.037–0.042 W.m⁻¹.K⁻¹, which is comparable with rock wool values of 0.033 – 0.046 W.m⁻¹.K⁻¹ [8].

Plant based materials have specific heat capacities of around 2.0kJ.kg⁻¹.K⁻¹, compared with only 1.0kJ.kg⁻¹.K⁻¹ for mineral based materials. This means that bio-based materials can store twice as much thermal energy as mineral based materials for comparable densities and thicknesses. The more heat a material can store, the slower it will respond to thermal changes. This thermal damping effect results in more stable internal room environments.

2.2 Light structural walls

Light structural walls have a dual function in a building, acting both as a weather-proof envelope and as insulation. As a general rule, they have poor load bearing capacity and are therefore combined with a structural frame, which is most often made from timber.

2.2.1 Straw Bale construction

Straw bale construction began in Nebraska, USA in the early 19th century, where the European settlers found few naturally occurring building materials. Stone and timber were in short supply, so they baled up grass, using them as oversized building blocks to form walls, and

plastered the faces with mud. With the advent of the Industrial Revolution, improved communications and mass production, brick, steel and timber became the building materials of choice and straw bale construction ceased to be used.

In the 1980s interest in straw bale construction was revived in the American West, and the technique has since permeated across the world. Examples can be found in Australia, China, Mongolia, Saudi Arabia, Mexico, Northern and Southern Europe and South Africa. In the Western United States, construction is at a level where local building standards have been developed to deal with the peculiarities of straw bale construction in California, Arizona and New Mexico. In France The RFCP (Réseau Français de la Construction en Paille) has developed a code of practice which has recently been submitted for approval to the national building regulation authorities, but there are currently no UK standards or codes of practice which relate specifically to straw bale construction.

The low carbon credentials of straw bale construction have encouraged research aimed at providing sufficient data and understanding of performance to allow it to be adopted more widely than just by the 'self build' community. Such research has been going on in many countries since the 1980s. Some of the publications emanating from this research are referred to here and are listed in the bibliography at the end of this chapter. They cover areas such as structural performance, fire resistance, resistance to decay, acoustic performance and hygrothermal performance. They also include case studies on building behaviour under different climatic conditions.

Constructing with straw has recently been developed into having the potential for high volume construction through the development of pre-fabricated systems. In the UK, ModCell is a locally manufactured structural timber frame infilled with straw bales and coated with a lime render on both faces. Similar systems are marketed in Belgium by Paille-Tech. The advantages of the pre-fabricated system include quality assurance, protection from rainfall during construction, and rapid on-site erection.

2.2.2 Straw-clay construction

Traditional construction technology for millennia, straw-clay construction can either be used in a monolithic form or as light earth blocks. Chopped straw is mixed with clay and water and tamped into shuttering. Once dry, the straw-clay is robust and durable, provided it is protected from water by a render, an impermeable plinth and good roof cover.

This technology offers less opportunity for high volume construction than straw bale, being more suitable for self-build or individual houses.

2.2.3 Hemp-Lime construction

Hemp-Lime construction began in France in the 1990s, initially as a substitute for wattle and daub repairs in

historic buildings. By 1993 buildings were being constructed in the southeast of France and in Brittany using a mixture of hemp shiv and lime cast around a timber frame. As the use of hemp-lime spread more widely through France, so techniques diversified. Hemp-lime is now available as pre-cast blocks of varying dimensions, and a spray application technique has also been developed, in addition to the most widely used technique of casting.

The use of hemp-lime in France is now well established, and a professional association has been formed, CenC (<http://www.construction-chanvre.asso.fr>), which encompasses members from all parts of the sector: researchers, farmers, manufacturers, practitioners, distributors, builders and designers. A set of guidelines has been published [9], and formal training is offered.

A International Hemp Building Association has been formed, based in Ireland, (<http://www.internationalhempbuilding.org/>) with the objective of promoting the use of hemp based construction materials worldwide. There is also a European Industrial Hemp Association (<http://www.eiha.org/>) aimed at supporting the cultivation, processing and use of hemp within the EU. The Hemp Lime Construction Products Association (<http://www.hemplime.org.uk/>) was set up in the UK "To promote the responsible development and use of hemp lime and associated products in the construction industry".

In the UK, hemp has been grown and processed since 1993. The majority of this processing was done by Hemcore Ltd (now Hemp Technology Limited), and was primarily for the purpose of fibre production for use in the automotive industry, with the shiv being sold for horse bedding. In response to the growing interest in hemp-lime construction in the UK, much of the shiv production is now packaged as Tradical® HF for use in hemp-lime. Hemp Technology has the capacity to produce 12,000 tonnes of fibre and 25,000 tonnes of shiv, equivalent to about 2500 houses per annum. In 2010 hemp-lime construction is expected to account for between 250 and 500 houses, so until demand increases substantially, it is unlikely that other production units will be commissioned to compete with existing production.

Competition within the binders used for hemp-lime is greater, since binders are used very widely in construction. Experimental work with a range of different binders showed that the shiv competes strongly with the binder for available water. This means that purely hydraulic binders such as cement or hydraulic lime are unable to hydrate completely, leaving a poorly bound, powdery core to hemp-lime walls. As a result of this, special formulations have been developed for use with hemp-lime based on air lime with varying proportions of additional hydraulic and pozzolanic constituents, and possibly additives such as surfactants. The most commonly commercially available binders are Batichanvre® (St Astier), Tradical® PF70, (Lhoist, mainland Europe), Tradical® HB (Lhoist UK) and Vicat Prompt® (Vicat). St Astier also offer their NHL2 binder for use with hemp.

The proportion of binder used in the mix controls the density, and hence also the thermal resistance, of the hemp-lime. In addition to this, it also controls the mechanical performance of the hemp-lime. However, the mechanical performance of hemp-lime is not directly related to the strength of the binder used [10]. The way in which the material is compressed during the casting process also controls thermal and mechanical performance.

As with straw bale construction, pre-fabrication is now being applied to hemp-lime construction. HemBuild®, a patented system developed in the UK, is now being marketed across the EU, conferring the benefits discussed above.

2.3 Paints and finishes

Bio-based paints have a number of advantages over conventional paints including:

- Flexibility, which allows expansion and contraction of the substrate without the paint cracking.
- Porosity, which allows the passage of moisture through the paint
- Ease of maintenance, allowing easy patching because the paints are breathable.
- Historical authenticity. Bio-based paints were used historically, so modern bio-based paints are more compatible for conservation and restoration of historic buildings.
- Low environmental impact through low embodied energy and low release of volatile organic compounds (VOCs), which reduced indoor air pollution

2.4 Floor Coverings

Bio-based materials are used on an industrial scale for flooring, particularly for linoleum and carpeting.

Linoleum is made from about 23% by weight of linseed oil, 30% wood flour, and 25% other bio-based materials. Virtually 100% of the components are bio-degradable, making this a very environmentally friendly material.

Carpeting can be made from sheep's wool, jute, sisal, coconut fibre (coir), sea grass, rush matting and bamboo.

2.5 Other materials

Other applications for bio-based materials include:

- Geotextiles made from bio-based materials are suitable for slope stabilisation, vegetation management and soil erosion control. They are significantly cheaper than synthetic materials.
- Thatch is a traditional roofing material which has a life expectancy of between 30 and 50 years. It is considered to be a 'warm roof construction' which does not require ventilation and will reduce energy consumption in use.

3 Carbon sequestration

Plant-based materials absorb atmospheric CO₂ through photosynthesis. This CO₂ is considered by many to be 'sequestered' within the material for its lifetime, and therefore to justifiably be deducted from the carbon footprint of the material. Materials such as coal and limestone also have sequestered CO₂, but since this was removed from the atmosphere more than 200 million years ago, it is not relevant to the current environmental crisis.

Hemp and straw will remove CO₂ from the atmosphere less than 12 months before the material is embodied within the structure of a building, and timber maybe 5 to 50 years previously. In both these cases, the CO₂ absorbed from the atmosphere is within a short enough time-scale to contribute to the reduction of current carbon emissions, provided always that the building has a planned lifetime of 60 to 100 years. This is of all the greater importance when these materials displace other, more carbon intensive materials.

A study of hemp-lime construction [11] calculated that a square meter of timber framed, rendered hemp-lime wall had a carbon footprint of -35.5kg CO₂ equivalent (CO₂e). In other words the CO₂ sequestered within the wall is 35.5kg CO₂e greater than the CO₂e embodied in the construction (materials, transport, energy input etc...). This compares with a carbon footprint of the UK traditional cavity wall brick and block construction system of around 110 kg CO₂e.

This concept of sequestration is an important one, but is not always accounted for when LCA is performed. For example, the Inventory of Carbon and Energy [12] acknowledges the concept of sequestration, but does not include it in its primary figures.

4 Vapour active materials

A growing area of interest is the hygrothermal performance of materials. Natural fibre insulation materials have the ability to create a breathable wall construction by readily absorbing and releasing moisture in response to changes in relative humidity and vapour pressure gradients in the surrounding environment. Heat flows are associated with these reactions. During absorption heat is released, and on desorption of moisture heat is absorbed [13]. This breathability produces a hygric damping effect, comparable to the thermal damping effect discussed earlier. When combined with the high specific heats associated with plant-based materials, and the thermal effects produced during sorption/desorption, materials such as hemp-lime demonstrate a 'virtual hygrothermal mass'. This phenomenon allows buildings to be constructed which consume less energy in use by lowering the requirement both for heating and for air conditioning.

5 Case studies

5.1 The BaleHaus

Research into straw-bale construction has developed in recent years in association with the commercial interest in large-scale mainstream straw-bale construction. Amongst other studies, the BaleHaus, (Figure 4) constructed on campus at the University of Bath, is perhaps one of the most informative.



Fig.4: The BaleHaus experimental building at Bath

The BaleHaus was constructed as part of a Technology Strategy Board (TSB) funded project and was subsequently disassembled and re-sited elsewhere on campus, where it is now part of a long term study, and being used as a dwelling house.

Wall et al [14] have used this building to identify the strengths and weaknesses of a pre-fabricated modular straw-bale constructive system. Studies included a life cycle assessment (LCA) [15], moisture content over 12 months, acoustic performance, air permeability and a thermographic survey.

The LCA was used to ascertain the environmental impacts of the prototype house compared with a hypothetical brick and block house with the same layout as the BaleHaus, which was used as a benchmark. Cradle-to-dismantling and cradle-to-grave analyses were used and revealed that the prototype house performs better than the conventional masonry house, especially in relation to its low global warming potential [14].

Moisture content of the straw in the walls was measured using wood moisture equivalent sensors, calibrated using data from Lawrence et al [15]. Over the 12 month period, the average daily moisture content never exceeded 22%. Prolonged moisture contents above 25% are considered to produce a significant risk of decomposition within straw [16].

Air permeability tests showed air leakages around windows, junctions between panels and inlet pipes. Once these leakages have been resolved, further testing showed an exceptionally low air permeability at 50 Pa of $0.86 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$.

Thermal imaging revealed a very good thermal performance with no sign of thermal bridging through timber frames, floor or roof.

As with all forms of construction, good detailing and high quality construction practice on site will ensure a high performance from a straw-bale building. With good detailing straw can be considered to be a robust and durable material, and the intrinsic low thermal conductivity of straw offers the opportunity for high performance buildings with low environmental impact.

5.2 Science Museum archive store

The Science Museum is a museum of science and technology that holds a collection of more than 300,000 items. When not being exhibited, these items are stored at a site in Wroughton in Wiltshire. This site, formerly a World War II airfield, primarily consists of extremely large concrete aircraft hangars. In order to store these artefacts in appropriate conditions, enclosures are constructed inside these hangars. Large amounts of energy are expended to maintain these enclosures at the desired temperature ($\sim 15^\circ\text{C}$) and humidity ($\sim 50\%\text{RH}$). This approach is seen by the trustees as being unsustainable, and they are actively seeking out alternative solutions.

Hemp-lime has the reputation for excellent hygrothermal buffering, and in 2012 the trustees of the Science Museum constructed an archival store made from hemp-lime. (Figure 5).



Fig. 5 : Archival store at the Science Museum, Wroughton

This building was commissioned in late 2012, and is now the repository for a large number of historic artefacts. An environmental control system has been installed, designed to support the passive environmental control provided by the hemp-lime. Environmental conditions are closely monitored externally and internally and energy consumption is also monitored.

Data from the archival store are currently being analysed, but it is noteworthy that between May 2013 and July 2013 the environmental control systems were switched off. During this period external conditions have varied from 0°C to 30°C and from 25% RH to 98% RH.

The archive store is kept closed, with infrequent entry by staff to maintain the collection, and during this period the internal conditions have varied by less than 1°C and 5%RH. For archival storage, the most critical factor is to avoid rapid changes in temperature and/or humidity since this sets up stresses within the material and causes accelerated decay. This performance is seen by the Science Museum as being extremely encouraging.

The system used to construct the archival store was a factory pre-fabricated one, which ensures zero defects and the highest quality of manufacture. When such a system is used, high performance buildings are much more readily constructed, and when combined with vapour active materials, there are increased opportunities for the creation of ultra-low energy, low environmental impact buildings.

6 Conclusion

Bio-based insulation material has the potential to revolutionise the construction industry. The use of renewable materials that sequester atmospheric CO₂, whilst at the same time offering the potential for passive environmental control means that buildings no longer need to account for up to 50% of global carbon emissions.

Since they are based on agricultural output, the technology is more readily transferrable to under-developed countries and offer the potential to displace steel and concrete, which seem to be the modern materials of choice.

A great deal more work needs to be done to ensure that bio-based insulation materials are adopted for high volume construction. All stakeholders need to be convinced of their robustness and durability, as well as their fitness for purpose, and their value for money.

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